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SOIL MOISTURE MEASUREMENT WITH THE NEUTRON METHOD

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CONTENTS

SOIL MOISTURE MEASUREMENT WITH THE NEUTRON METHOD

By

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1. INTRODUCTION

Many research locations have adopted the neutron method for the measurement of soil moisture content. This method has been used in irrigation, recharge, lysimeter, and watershed-management studies on the consumptive use of water by plants. As a result of this increased activity much additional experience with the method has been accumulated. Several questions regarding field procedure were answered by this research, though by no means has the method been perfected to the satisfaction of those concerned. Also, there have been changes in the design of the equipment that is now available.

In 1958 a report on the neutron method was published (14);[2] [3] but, because of the information acquired since then, it was desirable to prepare another report to bring the information on the neutron method up to date. This report provides information to those contemplating adoption of this method and to those who already use it but wish to improve their present techniques. Background information required for rational and successful use of the method is given. This report contains sufficient information to enable the individual investigator to choose the procedure best suited to his particular needs.

Data and information in this report are not confined to the experience of the writers. The experience of many others in the Soil and Water Conservation Research Division, as well as investigators in other organizations, is also reported. Pertinent facts have been assembled from published records, personal communications, and occasional conferences on this subject.

2. GLOSSARY

Alpha particle - Particle consisting of two protons and two neutrons; weight 4; charge +2; emitted by certain nuclei; also: Helium[4] nucleus.

Disintegration - Spontaneous emission by a nucleus of either alpha or beta particles.

Dose - Quantity of ionizing radiative energy absorbed by the body, or parts thereof, per unit of mass. Expressed in rem or mrem (roentgen or milliroentgen equivalent man). For gamma radiation 1 rem or 1 mrem is equivalent to 1 r (roentgen) or 1 mr, respectively.

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[2] Underscored numbers in parentheses refer to Literature Cited, p. 38.

[3] The 1958 report is out of print.

[4] An extensive glossary on radiation and radiological safety may be found in the "Radiological Health Handbook," published by the U. S. Public Health Serv. (13).

Dose rate	-	Intensity of absorption of ionizing radiation by the body. Expressed in rem per hour or any other appropriate time unit.
Flux	-	Number of particles crossing a unit of area per unit of time.
Gamma radiation	-	Electromagnetic, ionizing radiation emitted by the nucleus.
Half life	-	Time required to reduce the quantity of a radioisotope to one-half of the original amount.
Input sensitivity	-	Smallest signal that a system registers.
Isotope	-	Chemical element of a single atomic mass.
Mev.	-	Million electron volts: the kinetic energy imparted to an electron by a potential difference of a million volts.
Millicurie	-	A quantity unit of radioactive material equivalent to 3.7×10^7 disintegrations per second.
Milliroentgen	-	A unit of ionizing radiative energy; one thousandth of a roentgen.
Neutron	-	Elementary nuclear particle; mass 1; charge 0.
Radiation level	-	Intensity of ionizing radiation; expressed in roentgen or milliroentgen per unit time.

3. PRINCIPLES

3.1 Interaction of Fast Neutrons and Soil Water

The principle involved in the neutron method for measuring soil moisture is as follows: When a source of fast neutrons is inserted into a material capable of moderating, that is, slowing down, the fast neutrons, it will become surrounded by a cloud of slow neutrons. The density of the slow neutron in the immediate vicinity of the source is proportional to this concentration of the moderating material.

Generally, a small source of fast neutrons is obtained by intimately mixing an alpha emitter and beryllium. A Ra-Be pellet source is an example of such a mixture. Such a source emits about 16,000 neutrons per second per milligram (or millicurie) of radium. The energy of the neutrons emitted by such a source is not uniform, but ranges from less than 1 up to 15 Mev. (million electron volts). The average energy is around 4 Mev. The speed of such neutrons is about 1,000 miles per second.

When a fast neutron source is placed in moist soil the emitted neutrons interact with the surrounding medium. The emitted neutrons collide with the nuclei of the soil in a billiard-ball fashion; their direction is changed and they lose energy. With the energy losses, the speed diminishes until it approaches one that is characteristic for particles at the ambient temperature. For neutrons this is about 1.7 miles per second and the corresponding energy is 0.03 electron volts. Neutrons that have been slowed down to such a speed are called thermal, or slow, neutrons. Finally, the slow neutron is absorbed by the nuclei present in the soil and its existence terminates.

The moderating, or slowing-down, ability of nuclei present in the soil varies considerably. Actually, the moderating ability of all soil nuclei is small compared with that of hydrogen. In a collision with a hydrogen nucleus a neutron is slowed down very appreciably; the extent depends on the angle of collision. Therefore, if the soil contains a considerable amount of hydrogen, the neutrons are slowed down before they get very far from the source. The slow neutrons thus produced tend to be concentrated around the source.

The density of the slow neutron cloud that develops around the source in a hydrogenous material does not increase indefinitely, but it reaches an equilibrium value determined by the rate of thermalization and the rate of absorption by the medium. This equilibrium is reached rapidly--in about a millionth of a second--after a fast neutron source is inserted in the hydrogenous material. Some soil elements have an unusually high absorption capacity for slow neutrons, for example, cadmium, boron, and chlorine. Their presence tends to decrease the density of the slow neutron.

It is apparent from the foregoing that if the medium surrounding the source is low in water content, and therefore has less hydrogen, the cloud of slow neutrons is less dense and extends farther from the source than if the medium is high in hydrogen content, or water content. Thus, it is possible to measure the moisture content of the soil by observing the density of the slow neutron cloud that develops around the fast neutron source when it is inserted into the soil.

This method gives a direct measurement of the moisture content by volume since the presence and the weight of other soil elements are, generally, not significant. In the first approximation the relationship between slow neutron density and moisture content by volume is linear. This can be predicted, to some extent, by theoretical considerations and is also apparent from experimentation. In actuality, calibration curves generally deviate from a perfectly straight line; the amount of deviation depends on the shape and size of the equipment that is used. An example of a calibration curve is shown in figure 1.

In the foregoing it has been assumed that hydrogen in soil is solely the result of the presence of water. In reality, this may be far from true. Hydrogen may be present in appreciable quantities as an integral part of clay crystal lattices or of amorphous, colloidal material. Also, organic matter in the soil contains hydrogen. However, differences in calibration due to the presence of nonwater hydrogen have been difficult to demonstrate experimentally. The true cause of this anomaly has never been entirely established. It is possible that the energy reduction that neutrons sustain when they collide with hydrogen, particularly at low speeds, is dependent upon the chemical binding of the hydrogen in such a way that hydrogen which is a part of large molecules or of extended clay lattice structures behaves as if it had a higher atomic number. Consequently, the colliding neutron may lose little of its energy.

The interaction between fast neutrons and soil water is independent of such environmental factors as temperature and pressure. It is affected very little by salinity, chemical composition of the soil, or the degree of binding of the water by the soil particles (5). This implies that the neutron method will have wide general applicability and that corrections in its use generally are not necessary.

The boron content of soil in certain instances is sufficiently high to interfere with the method. A high boron content results in a lowered slow neutron density, because boron is a very efficient absorber of slow neutrons. This is also true, but to a lesser degree, of chlorine. A total boron content of the soil in excess of 10 parts per million by weight and a total chlorine content of the soil in excess of 1,000 parts per million by weight would cause measurable reductions in the slow neutron density and appropriate corrections might have to be made.

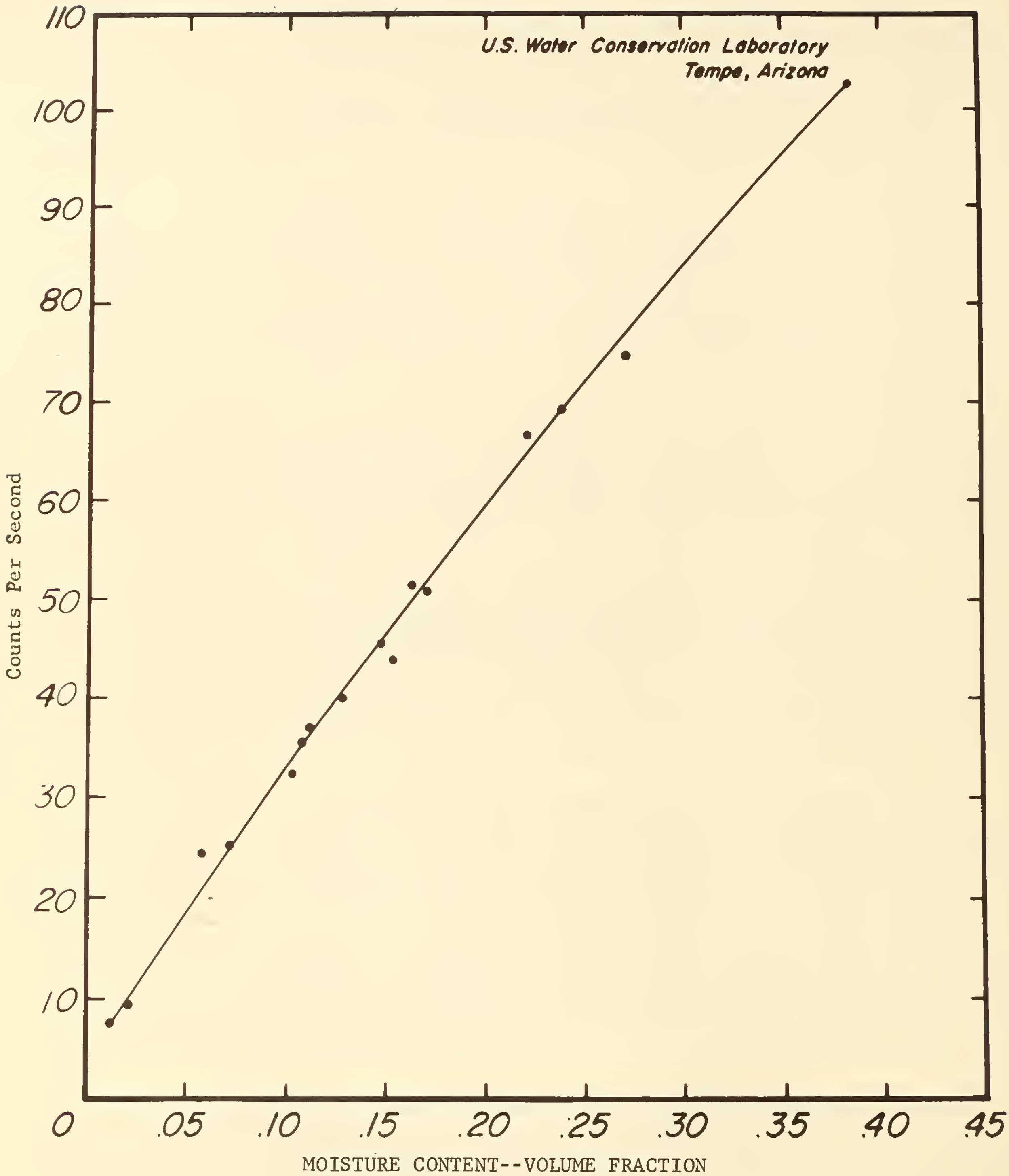

Figure 1. --Example of a calibration curve of a neutron moisture probe. (From (16).)

3.2 Sources of Fast Neutrons

Even though several fast neutron sources can be used, it is customary to use a Ra-Be source in the slow neutron method for measuring soil moisture. The principal advantages of a Ra-Be source are (1) the half life is long--around 1,620 years--and no correction for decay is required; (2) their ready availability, exemption from AEC license, and inexpensiveness (about $200 for sources between 1 and 5 mc.); and (3) their small physical size, which makes them, therefore, easily incorporated into a field instrument.

The major disadvantage of using Ra-Be as a fast neutron source is the health hazard associated with its use. First of all, in the decay of radium, radioactive radon gas is produced, which makes it essential that the source be perfectly encapsulated. Escape of radon gas would result in a serious health hazard and would also affect the source itself, since the alpha particles required for the neutron emission originate in part from radon and its decay products. The use of a Ra-Be source is therefore predicated on a perfect seal of the source container. A periodic leak test is essential and is required by the Department of Agriculture.

A further hazard associated with the use of a Ra-Be source is the gamma radiation that results from the decay of the radium and its daughters. To further illustrate this point, the gamma radiation level per millicurie Ra-Be is about 9 mr. per hour at a distance of 1 foot and 2 mr. per hour at a distance of 2 feet. These figures apply in the absence of any shielding whatsoever. These radiation levels are not considered excessively high. Nevertheless, they would result in exposures in excess of the maximum permissible figure if a Ra-Be source was used regularly without any shielding. Any probe design, therefore, includes a certain amount of shielding to permit handling the probe without undue exposure. Any handling procedure provides for the storage of the probe in an additional shield, which will result in further reduction of the radiation hazard. It is possible that in the future neutron sources will be used that have all the advantages of the Ra-Be source but a much reduced gamma emission. For example, Pu-Be is now in limited use.

All other things being equal, the slow neutron density around the source is directly proportional to the neutron emitting strength of the source. Since the neutron emission is again directly proportional to the amount of radium in the source, the source strength is usually described in terms of the millicuries of radium that went into the manufacture. Sources ranging from 1 to 20 mc. have been used in soil moisture neutron probes. The determination of the lowest possible activity that will result in sufficient accuracy will be discussed in sections 4.1 and 6.2.

3.3 Counting of Slow Neutrons

Neutrons are uncharged particles, and therefore they can only be detected by engaging them in a nuclear reaction that results in a charged particle. In turn, the latter can be counted by the usual techniques of discharge in a gas counter or by scintillation counting in a solid or liquid scintillator. Although several possibilities exist, the one that has generally been used in the slow neutron method for measuring moisture is to insert a gas-filled counter that contains a certain amount of boron trifluoride gas in the slow neutron cloud around the source. Since the density of this cloud varies with distance from the source (sec. 3.1) the geometric relation between source and counter should be fixed for reproducible measurements. This is accomplished by assembly of the source and counter into a single unit, usually referred to as a probe.

A boron trifluoride counter is a cylinder filled with enriched boron trifluoride at a pressure of 20 to 30 cm. mercury. The term "enriched" means that a higher proportion of the boron-10 isotope is present in the boron of the gas than in natural

boron, which consists of 18 percent B^{10} and 82 percent B^{11}. Boron-10 is highly effective in absorbing slow neutrons and in so doing emits an alpha particle that sets off the counter. The counter is provided with a central wire, which is insulated from the brass wall. A high voltage drop is maintained between the central wire and the wall. When an alpha particle is produced as the result of the nuclear reaction between the slow neutron and the boron in the boron trifluoride, it ionizes the counter gas and a discharge pulse results.

The potential difference between the central wire and the counter wall is between 1,000 and 1,500 volts. By comparison, the discharge pulse is very small--from 1 to 5 mv.--and very short. The measurement of the density of the slow neutrons consists, then, in detecting and counting the number of discharges per unit time.

Since the pulse duration is very short, the counter can count many pulses per second without showing so-called coincidence loss caused by the partial or complete overlap of pulses. In actual practice, counting rates are rarely higher than 500 counts per second--far below the rated capacity of the counter. While each count represents the elimination of a B^{10} atom of the gas with which the counter is filled, the number of B^{10} atoms in the counter is so large that the device can be used almost indefinitely. The inert gas that is also in the counter will be depleted by ionization long before the boron-10 is used up. Failure of BF_3 tubes is rare and is usually the result of the development of a leak in the counter and consequent loss of counting gas.

Since the process whereby the BF_3 counter pulses are produced is a nuclear reaction, the effect of temperature and other environmental factors upon the count rate or performance is immeasurably small and no correction is required.

Counter pulses can be caused, in addition to those stemming from neutron-boron interactions, by cosmic radiation and by gamma radiation emanating from the radium in the Ra-Be source. Pulses produced by cosmic radiation are of about the same magnitude as those produced by neutrons and cannot be distinguished from them. Furthermore, they cannot effectively be eliminated by shielding and such counts are always present as an inevitable background, which, fortunately, is quite low compared with the usual counting rates. The gamma-caused pulses are present in comparatively large numbers, but their energy is less than that of the pulses produced by neutron interactions. The counting mechanism must, therefore, be able to separate the gamma from the neutron-induced pulses.

Since the voltage required for the operation of the counter is relatively high, good insulation must be maintained both at the counter and in the connectors and cable leading from the counter to the high voltage supply, which is usually a part of the instrument used to obtain a record of the counting rate. Faulty insulation results in spurious discharges, highly irregular counting rates, or both. Exclusion of moisture is essential in maintaining sufficient insulation.

3.4 Counting Equipment and Counting Statistics

Relatively speaking, the pulses that are produced at the BF_3 counter are small. Preamplification to a level between 0.1 and 1 volt is necessary before the pulses can be conducted for more than a few feet to the apparatus used for determining the count rate. This may be accomplished by incorporating a small preamplifier with the source counter assembly. The amplified BF_3 pulses, which include both gamma- and nuetron-induced pulses, are then conducted by means of a coaxially shielded cable to the equipment that determines the count rate. Such equipment consists of three essential parts. First, there is an amplifier to amplify the pulses even further. Second, there is a device that admits the neutron-induced pulses to the counting circuit but not the low energy, gamma-induced pulses. Such circuitry is usually called a discriminator and it acts as a threshold. The energy level of the

threshold is usually referred to as the sensitivity, and often the sensitivity, or threshold level, is adjustable. By trial and error the sensitivity is adjusted until no, or a very small proportion of, gamma-induced pulses are admitted and all, or practically all, of the neutron-induced pulses are counted.

There are two forms of the third part of the apparatus to determine the count rate. One form is a scaler in which the total number of pulses is registered (fig. 2). In addition to determining the total number of pulses, one must also determine the time over which they were accumulated in order to determine the count rate. Although this can be done manually, most scalers have a built-in timer that turns on the scaling circuits when started and turns them off when the timer has run for a preset period. Division of the total counting time into the number of counts registered gives the counting rate. Thus, the scaler must measure both time and accumulated count.

The other form for the third part of the circuitry is a rate meter (fig. 3). In a rate meter the counting rate is determined directly and can be read from the dial of an indicating meter. However, it does take a certain amount of time for the meter to register a counting rate from which there will be no further systematic deviations. The rapidity with which this takes place is indicated by the so-called time constant of the rate meter, and a rule of thumb is that the final indication will be reached in about 5 time constants. The rate meter circuit is generally designed and operated in such a way that there exists an acceptable compromise between the stability of the

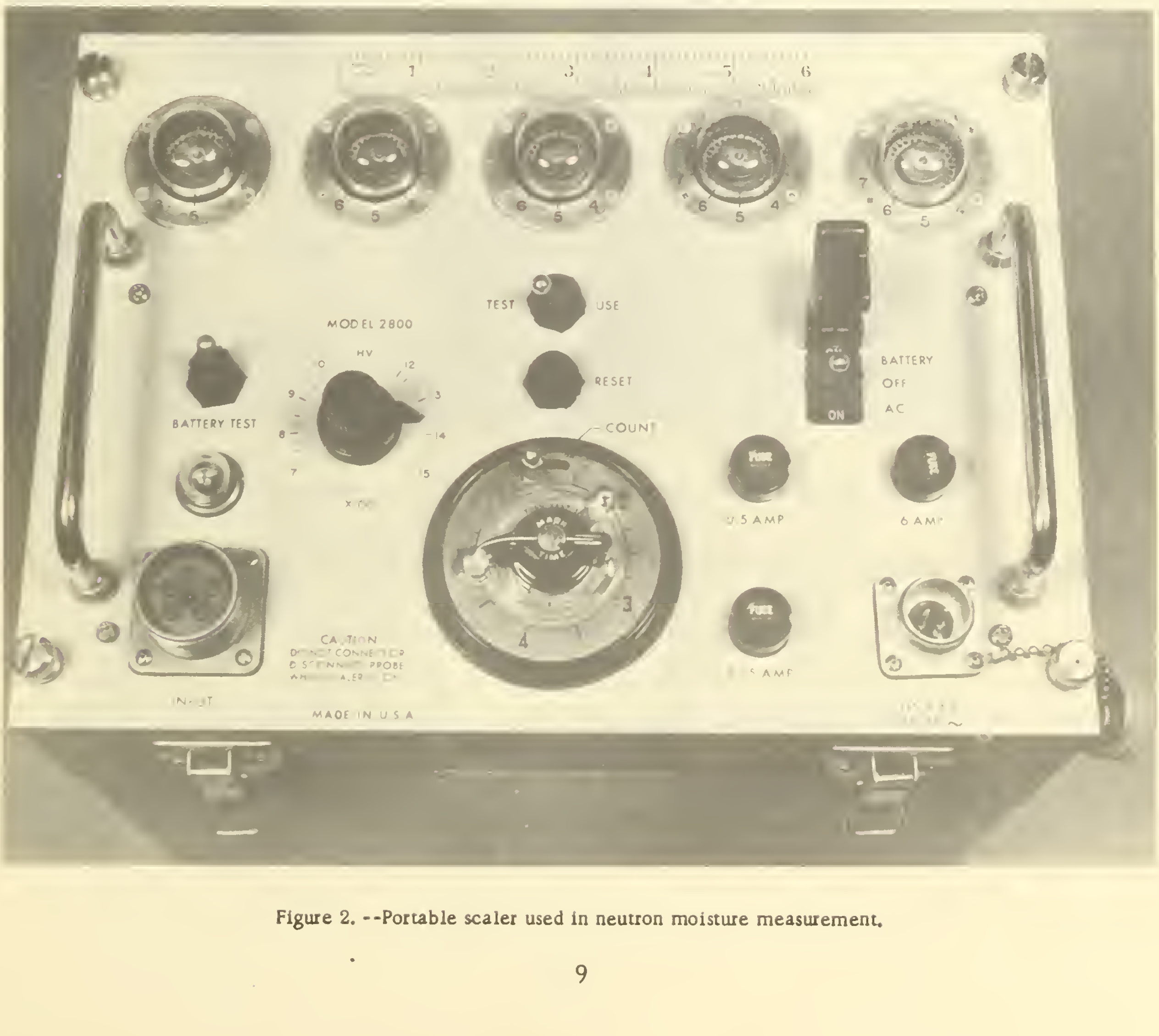

Figure 2. --Portable scaler used in neutron moisture measurement.

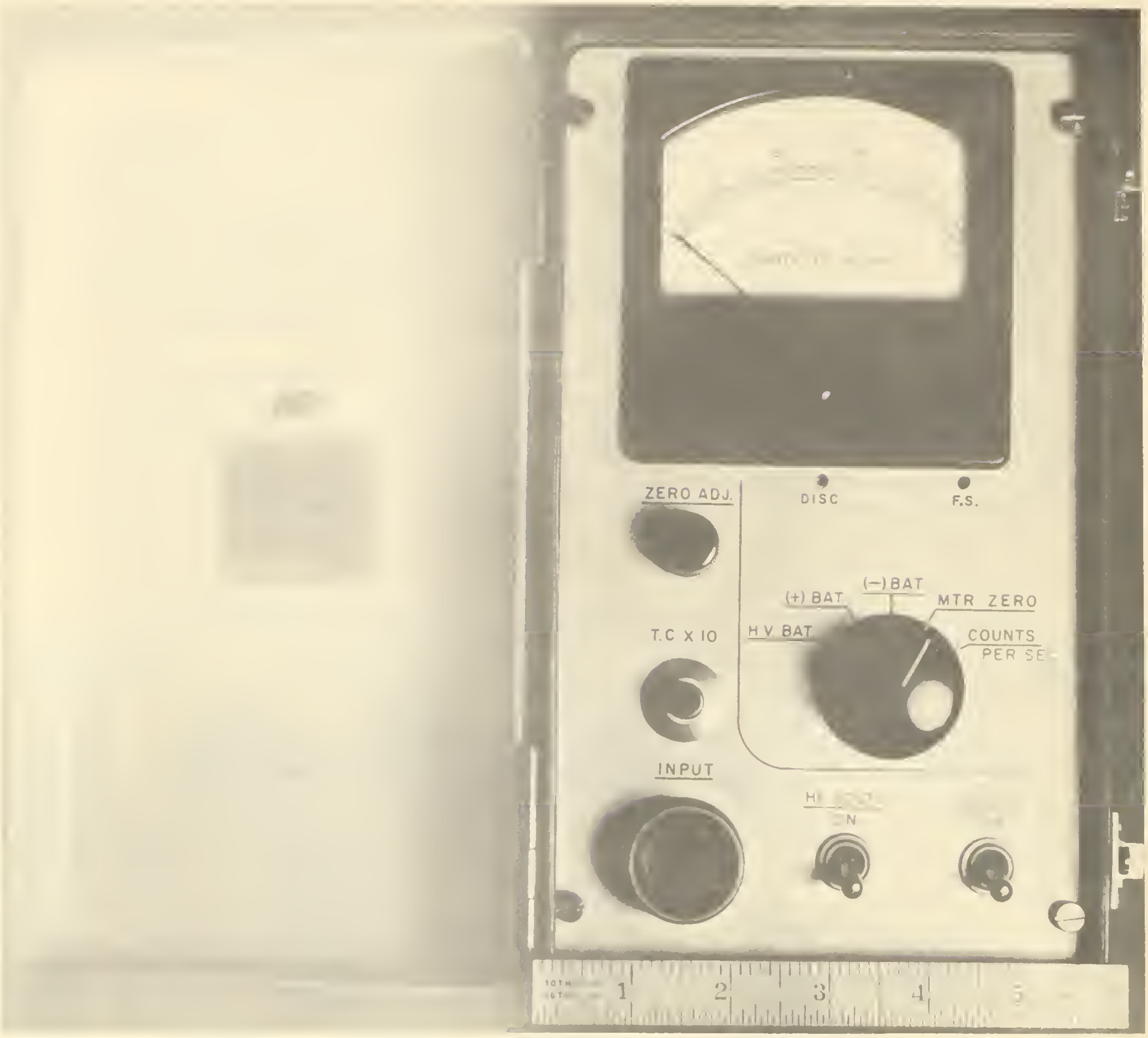

Figure 3. --Portable, lightweight rate meter used in neutron moisture measurement.

needle indication and the amount of time that is required to reach the equilibrium position.

It is of interest to consider the precision that may be obtained with scalers as compared with rate meters. When determining the count rate by accumulating counts over a known period of time, the standard error equals the square root of the total number of accumulated counts. When a scaler is used, and if we assume that the elapsed time is measured without appreciable error, the standard error of the counting rate is equal to the square root of $\underline{N}/\underline{t}$ in which $\underline{N}$ is the counting rate and $\underline{t}$ the period over which it was measured. For example, if 10,000 counts are accumulated in 4 minutes, the counting rate is 2,500 counts per minute and its standard error 25 counts per minute. The associated fractional error is then 1 percent.

If a rate meter is used with a time constant so that the equilibrium value would be reached within 1 percent after 4 minutes the appropriate formula shows that the fractional error is 1.5 percent. If a small time constant is used at first and then a larger one, it is possible--within the same amount of time--to reduce the fractional error even further. Hence, within the same amount of counting time, an equally accurate indication may be obtained from a rate meter as from a scaler. One-minute counts obtained with a rate meter and a scaler are compared in figure 4.

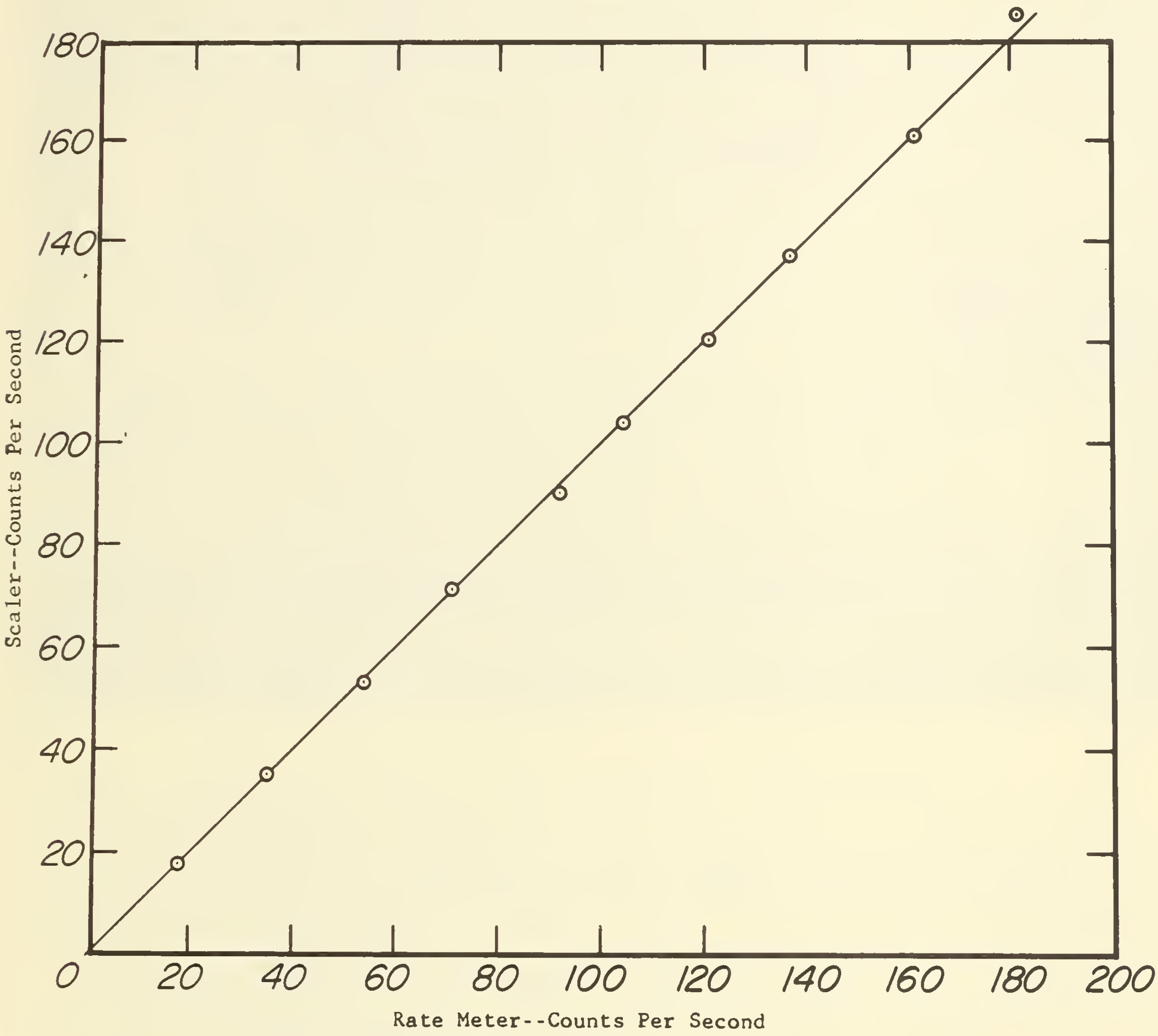

Figure 4.--Readings of neutron count rate obtained with a rate meter compared with those obtained with a scaler.

The precision of a rate meter, however, is ultimately restricted by the precision of the indicating meter. Generally, the error of indicating meters is between 1 and 2 percent of the full-scale range. Thus, it is concluded that a rate meter is never more accurate than about 1 to 2 percent of its full-scale indication and that it is possible to obtain greater precision with a single reading with a scaler, provided one is willing to spend additional counting time over and above that required to get a stable rate meter reading. Repeated rate meter readings also give a more precise average.

In the practical implementation of the neutron method the amount of time that can be spent on a single observation is often dictated by other considerations. Within the available time, results that are sufficiently accurate in terms of moisture content can be obtained with either a rate meter or a scaler.

3.5 Depth and Surface Methods

The neutron method can be adapted to measure soil moisture of the subsurface of surface soil strata. Measurement of the subsurface soil is accomplished by inserting a measuring probe and of the surface soil by placing a suitable device on the soil surface. However, the principles are the same.

In the depth measurement the probe--consisting of source, counter, and preamplifier--is cylindrical in shape so that it is possible to locate it in an access tube or well. The access well severely modifies the configuration of the moderating surroundings of the source, but it does not invalidate the method. In any event, it is necessary to obtain an empirical calibration relationship between moisture content and counting rate (see section 5.1). However, it also follows that the size, shape, and material composition of the access tube must be identical from one measurement to the other. It is not possible, therefore, to use different sizes or wall thicknesses of access tubing indiscriminately. Also, the calibration must be carried out with exactly the same type of access tube as will be used for the field measurements. The size and shape of the access tubing not only affects the count rate itself but also the shape of the calibration curve. It is not possible, then, to use "correction factors" or other means to translate data obtained with different access tubes from one to the other.

Such a problem does not arise when the neutron method is applied to measuring surface soil moisture. In principle, all that is required for this measurement is to place a source and a counter side by side on the surface of the soil in such a way that their position, relative to the surface, is always the same. It has been found, however, that this procedure is not very efficient (17) because numerous fast neutrons are lost to the atmosphere and are not utilized in the measuring process. To obtain adequate precision an impracticably large neutron source would have to be used. This difficulty can be overcome by using several neutron counters instead of one. Another, and simpler, method is to cover the source counter assembly with a shield containing hydrogenous material such as paraffin, water, or plastic (fig. 5). The containment of fast neutrons in the immediate vicinity of the soil surface by this means results in marked efficiency. With this method sufficiently high counting rates can be obtained with a single neutron tube and a source no stronger than one would ordinarily use in the depth method.

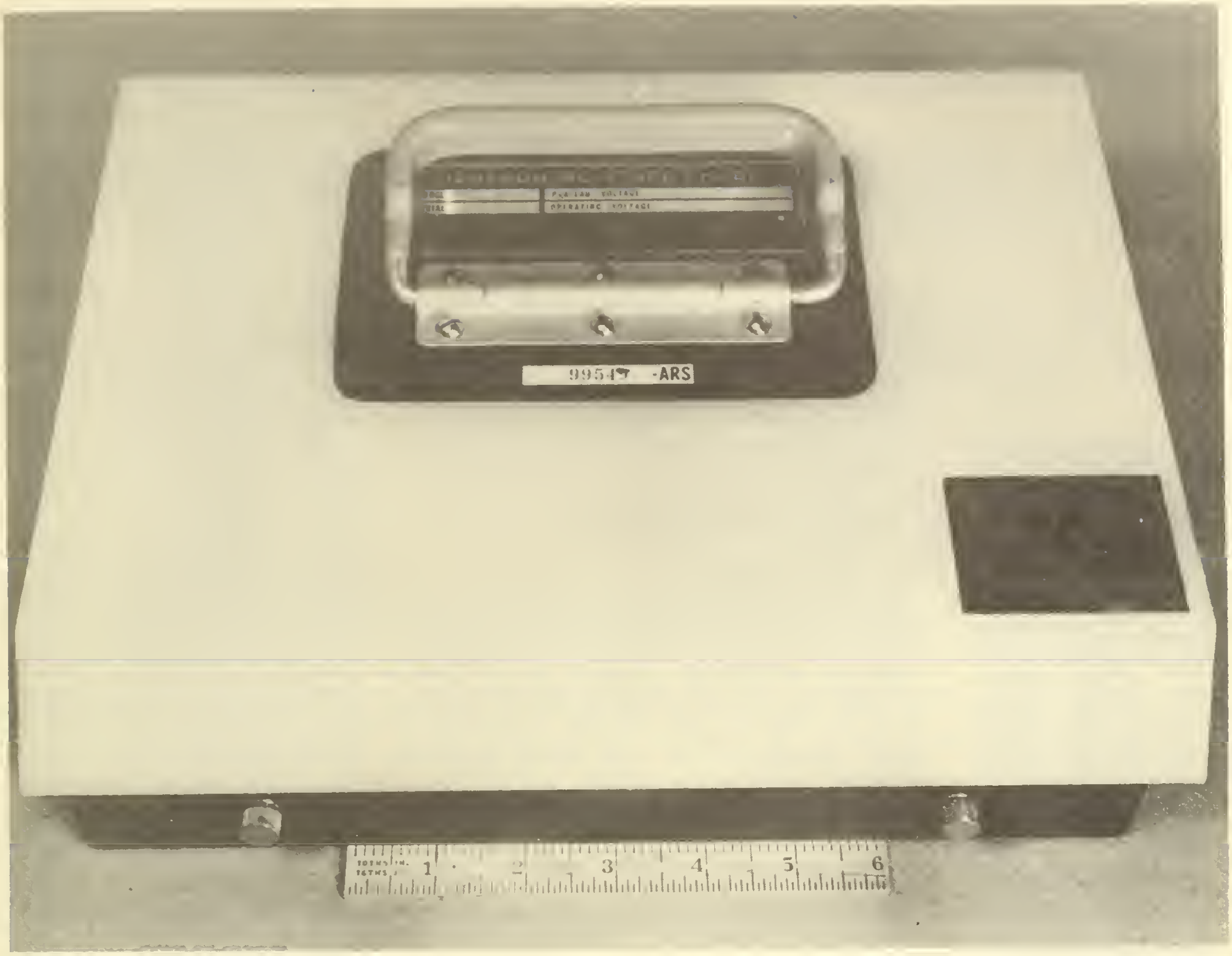

Figure 5. --Simple surface probe, with a single counting tube and plastic shield.

4. EQUIPMENT NEEDS

Based upon the discussions in the previous section, a further elaboration of the equipment needs and requirements to carry out measurements with the neutron method will now be presented.

4.1 Source-Counter Assembly (Probe)

4.1.1 Depth Measurements

Since the depth measurement is obviously best carried out in a cylindrical pipe or tube, the probe is designed to fit as closely as possible without any danger of getting lodged in the access pipe. This generally requires a clearance of at least 0.010 inch all around.

There are two ways of assembling the probe with respect to the mutual position of the source and counting tube. One method is to attach the source to the side of the counting tube in the approximate center (fig. 6). Since the neutron cloud is centered around the neutron source, it would seem obvious that the counting device itself also should be centered with respect to the source. However, the center arrangement

results in inefficient use of the available volume in the access tube for slow-neutron counting. Therefore, positioning of the source and utilization of available space are two opposing effects that determine the counting rate.

The other method--which is the simplest and, historically, the oldest--is to attach the source to the end of the counting tube (fig. 7). Although at least half of the theoretically available counts are wasted, one can utilize the entire available space for the sensitive volume of the BF_3 counter. With both methods it is convenient to locate the preamplifier on top of the counter.

All other things being equal, it has been shown experimentally (16) that the end arrangement is about twice as efficient as the center arrangement, in terms of counts per millicurie. This implies that under otherwise identical conditions the precision obtained with the end arrangement is about 1.4 times greater than the precision that is obtained with the center arrangement. For equal precision only one-half the Ra-Be source would be required with the end arrangement as would be required with the center arrangement. A comparative diagram of the two arrangements is shown in figure 8.

The entire probe should be of rugged construction because it is handled frequently and moved up and down in the access pipe. It is also very important that the probe be entirely sealed against moisture. Sudden temperature changes may cause condensation on the outside of the probe, and such moisture might find its way to the inside. Other sources of moisture are rain, fog, perspiration, and water standing in the access pipe. The use of positive moisture seals, such as 0-rings, is highly desirable.

The outside diameter of a neutron probe is another critical factor. As the outside diameter increases the counting rate increases, because of the greater volume available for the BF_3 counter. But the modification created by the access tube becomes greater and ultimately reduces the counting rate again as the access tube becomes wider. An additional consideration is the cost and installation of the access tubing. Both cost and labor of installation rise as the outside diameter of the access tubing increases.

The length of the probe is not critical except that it does influence the nature of the calibration curve. It has been shown that the physical extent of the sensitive volume, or detecting device, has some bearing on the shape of the calibration curve. Long sensitive volumes result in concave calibration curves that show loss of sensitivity at high moisture contents; very short detectors show convex curves that imply loss of sensitivity at

Figure 6. --Neutron probe in which the source is located at the side.

low moisture contents. Experience has indicated that a detector 4 to 6 inches long results in a calibration relationship that is nearly linear. In turn, this dimension will generally determine the total length of the probe.

Thus, the mutual position of counter and source, as well as the configuration of the counter itself, are major factors determining the count rate at any given moisture content. Furthermore, these factors influence the shape of the calibration curve. Therefore, calibration cannot be transferred from one type of probe to another. Probes that are made according to the same pattern, even though they may differ in the strength of the source, and the efficiency of the boron trifluoride tube, exhibit the same calibration curve when referred to a suitable standard.

4.1.2 Surface Measurements

Much of the design considerations applying to a depth probe also apply to a surface probe. The observed counting rate depends upon the moisture content of the underlying soil and on the source strength. Furthermore, it is determined by the total amount of active counting volume and the mutual arrangement of source and counter. A further consideration is the degree to which the probe conforms to the surface. A slight degree of roughness or separation of the probe from the soil surface results in appreciable lesses in counting rate (15). Therefore, surface probes can only be used on a carefully smoothed surface. It is essential then, as it is in the depth measurement, that all these design factors, basically geometrical in nature, be held the same in order to make meaningful measurements with a probe that has been previously calibrated on soil moisture standards. The most efficient arrangement is one in which the source is as close to the soil surface as possible and the BF_3 counter or counters are in its immediate vicinity. It has been pointed out that a hydrogenous shield over the source counter assembly materially increases the counting efficiency. Whether this arrangement results in a change in soil depth sampled, as compared with an unshielded arrangement, is not known.

4.2 Count Rate Determination

As indicated earlier, it makes little difference in principle whether the count rate is determined with a scaler or a rate meter. The instrument must have

Figure 7. --Neutron probe in which the source is located at the end.

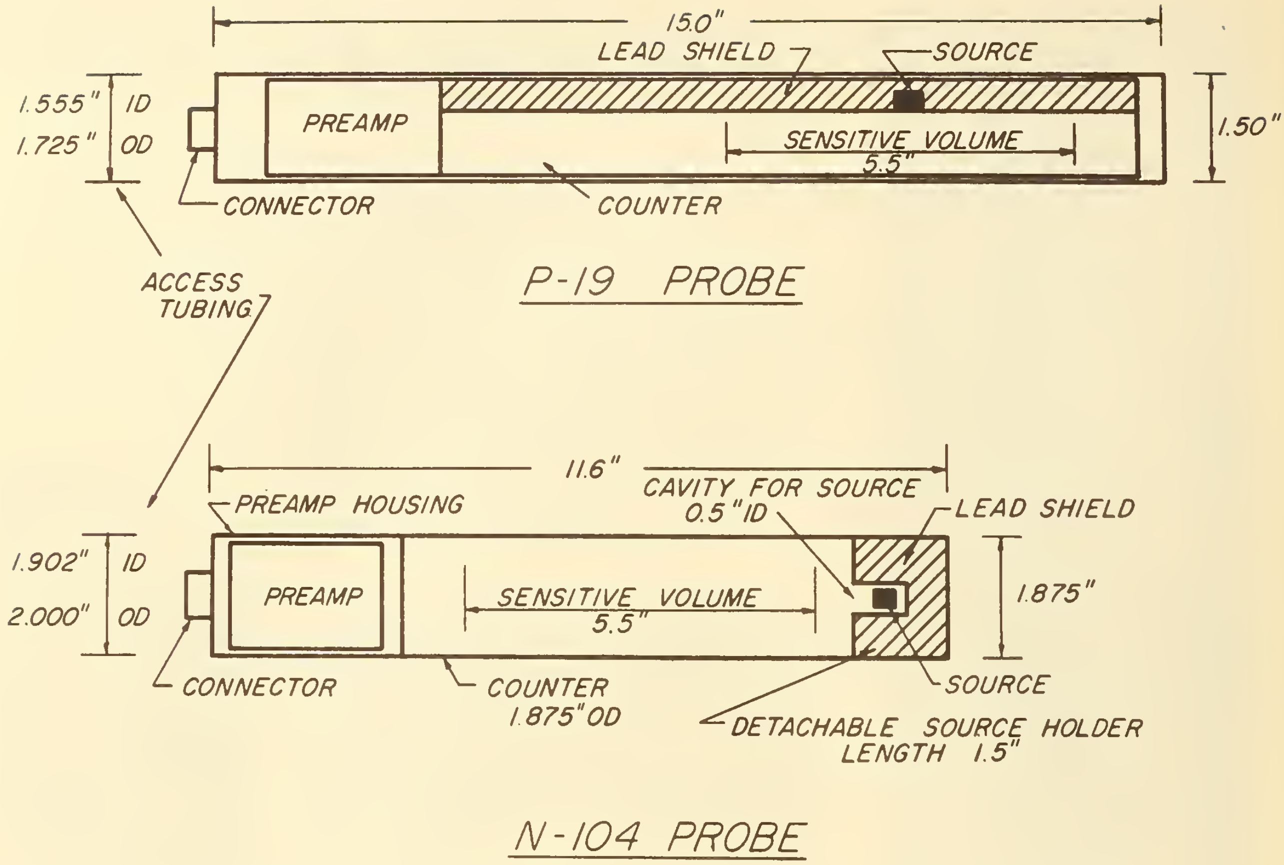

Figure 8. --Comparative diagrams of side and end arrangement of the source in a neutron probe.

the following characteristics: (1) It should be portable and self-contained; (2) its weight should not be in excess of what a person can carry conveniently in rough terrain under adverse conditions for a considerable period of time; (3) it should provide a stable source of high voltage to operate the counter as well as the low voltage required to operate the preamplifier; (4) its operation should not be appreciably affected by ambient temperature within a reasonable range; (5) it should be sufficiently rugged to withstand transportation in vehicles; and (6) it should be sealed to exclude moisture and dust.

Since the high voltage requirements for maximum count rate and satisfactory discrimination between the gamma and neutron pulses may vary somewhat from one BF_3 tube to another, the instrument should provide a means to adjust the discrimination level. The optimum level may be set by manufacturer or supplier, but it is well to verify this setting experimentally. This may be done by suspending the probe in air so that no moderating material is in the immediate vicinity. The discrimination level, or input sensitivity, is then adjusted so as to obtain a counting rate from 10 to 25 counts per minute per millicurie of radium used. It is not possible to exclude all counts in air without, at the same time, reducing the number of neutron pulses.

In the use of a scaler one must time its operation either by hand with a stopwatch or by means of a timer that provides the stop-and-start signal for the counting procedure. A timer used for this purpose should have a precision of better than 1 percent. The timer is, ultimately, the limiting factor in the accuracy of the count rate measurement made with a scaler. It is extremely important to verify the

characteristics of a timer at periodic intervals and, also, to confirm that it operates independently of ambient temperatures and humidity.

A rate meter is simpler to operate than a scaler, since it has no timing device. The time constant should be selected and manipulated to get an equilibrium value within the observation time and, simultaneously, to obtain a meter indication that is sufficiently stable for easy reading.

4.3 Cables and Connectors

By far the most troublesome part of the entire instrumentation is the connection between probe and count rate meter, or scaler. The cable must not only provide the proper connections and be adequately shielded against pickup of external noise, but it should also be strong enough to support the probe; it should be flexible when exposed to all prevailing temperatures, sunlight, and various forms of dirt. A particularly troublesome spot is the transition from the cable to the plug, which is required to connect the cable to either probe or instrument. Frequent flexing of the cable near the plugs results in cable separation. This will be evident in operation by erratic count rates, absence of any signal, or extremely high counting rates. The difficulty may be intermittent, and can then only be verified by flexing or jiggling the cable at either of the two connectors. Hence, it is important that cables be interchangeable and that they be provided with good connectors that are moisture-proof and preferably permanently connected to the cable by means of some potting or molding technique. It is highly advisable to have one or more spare cables on hand when the instruments are used in the field.

Most commonly used cables range in length between 10 and 20 feet. No difficulty has been encountered with cables as long as 200 feet. Just how long cables can be made with existing electronics is not known. An additional feature desirable in connecting cables is that they not be too elastic. When measurements are made frequently at considerable depth it may be hard to locate the probe precisely with regard to the surface if the cable has stretched. Elasticity depends somewhat on the ambient temperature.

4.4 Standards

If all conditions set forth in the previous sections with regard to the probe and the counting rate instrument are fully met, the use of standards would be entirely superfluous. Usually this is actually so. However, it is extremely reassuring to the investigator if he can determine whether his equipment is in perfect working condition. This can be done rather easily by means of a suitable standard.

Although various forms have been constructed, all standards consist of a cylindrical body provided with a suitable piece of access tubing down the center; the body itself consists for the most part of some hydrogenous material, such as water, paraffin, wax, or plastic (fig. 9). The depth probe must be inserted in this standard in a reproducible manner and the count rate determined. If one wishes to refer the counting rate to a standard and to work with ratios rather than absolute counting rates, the precision with which the ratio is determined is improved by providing a standard yielding a high count rate.

Similar considerations apply to a suitable standard for a surface probe. If the surface probe is not provided with a hydrogenous shield, the standard should consist of a slab of hydrogenous material such as lucite, nylon, or paraffin upon which the probe is located to determine the standard count. If the surface probe has a hydrogenous shield as a permanent feature, the shield itself can be used as a standard by merely suspending the entire probe, including its shield, in the air. Usually a distance of 12 inches above the soil surface will suffice for this purpose.

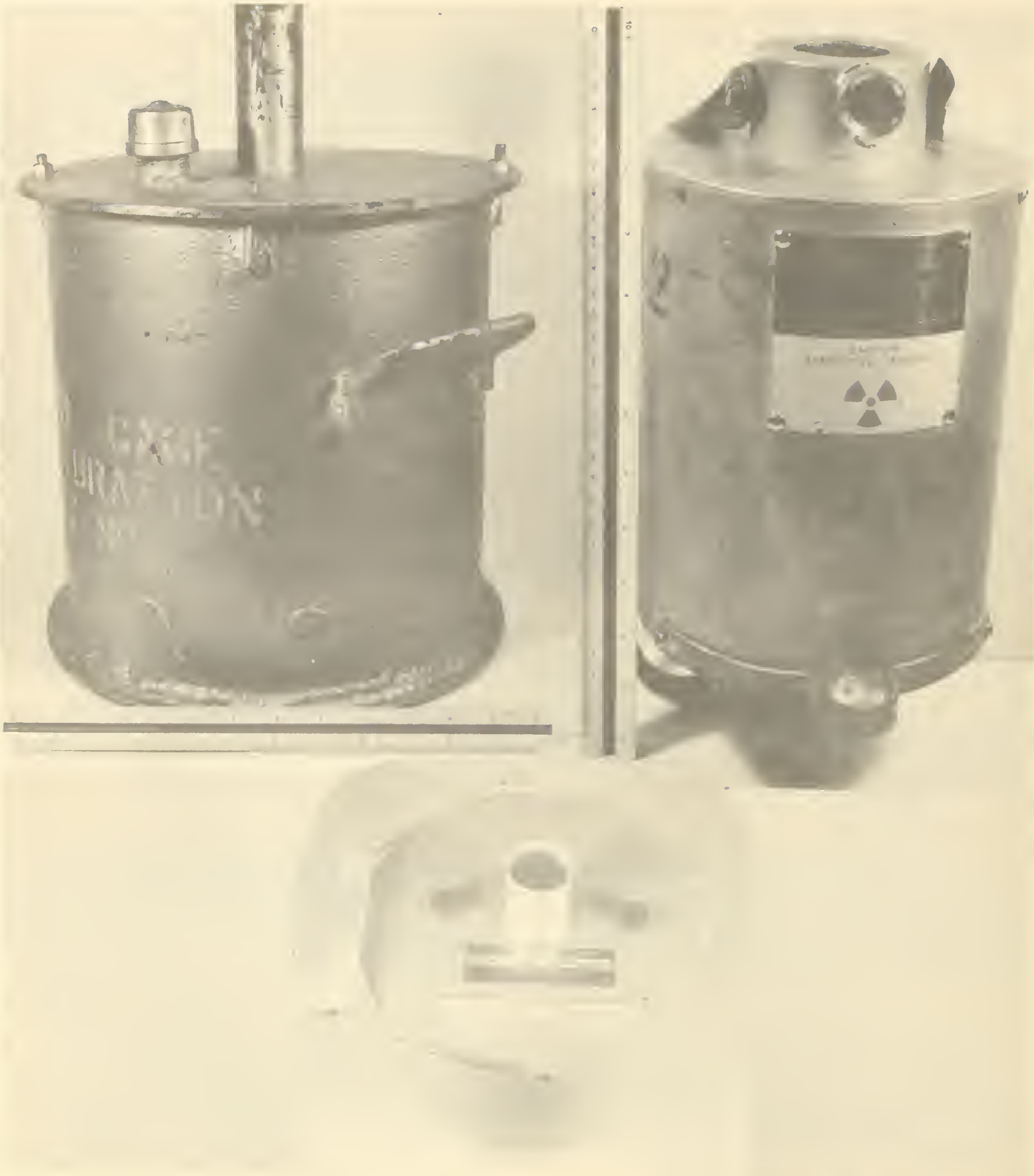

Figure 9. --Standards for neutron probes: Upper left, paraffin and sand standard; upper right, paraffin standard; bottom, water standard.

4.5 Radiation Monitoring

An essential part of any program involving the use of the neutron method is the procurement and use of equipment to detect and record the radiation level and personnel exposure.'Such equipment may include a survey meter for monitoring the radiation field and pocket dosimeters and film badges for recording the exposure of personnel. See also section 9.

4.6 Selection of Source Strength and Accuracy of the Method

Before procuring equipment for utilizing the neutron method for measuring soil moisture, some thought must be given to the proper selection of the source strength. Since a Ra-Be source constitutes a health hazard, it is imperative that it be as small as is compatible with the requirements for accuracy that are needed. The accuracy of the method is in part determined by the count rate that is obtained, the latter being directly proportional to the source strength. Therefore, it is necessary to discuss the accuracy that can be obtained with the neutron method prior to showing how the appropriate strength of the Ra-Be source may be determined from such considerations.

The use of the slow neutron method is in every instance predicated upon relating the observed counting rate to a measured moisture content--an experimental calibration. For the purpose of this discussion it is assumed that this relationship is linear. However, if it were slightly curvilinear, the same reasoning would still apply.

Even if, in the calibration procedure, the counting rate was determined without any appreciable error--through the use of a strong source, long counting times, or both--the points representing different moisture contents and the associated counting rates would not lie perfectly on the surmised linear relationship. This is not due to imperfections in the neutron method or the equipment used therein, but is attributable to random errors made in determining the moisture content of the standards. Generally, the measurement of the moisture content involves both a determination of volume and a determination of moisture content by weight. Both of these, in particular the determination of a volume, are subject to experimental error. Furthermore, owing to the inevitable variability of soil moisture content on a volume basis, even within a carefully prepared standard there is sampling error. Thus we find, upon statistical analysis of the calibration relationship, that there is a standard error of regression associated with each point, to be attributed solely to the errors of the soil moisture measurement.

After calibration, the relationship as established is then used to translate a counting rate into a moisture content. Because of the error that is involved in determining the moisture content of the standard samples and the ensuing uncertainty in the definition of the calibration relationship, there results what is usually called an error of prediction. This error is the deviation of the derived soil moisture content from the true moisture content in the absence of any error in the determination of the counting rate. This error of prediction determines the maximum permissible error involved in determining the counting rate. An efficient experimental procedure generally results if one attempts to make all error components of nearly the same order of magnitude. In this particular instance, the calculation is based upon stipulating that the maximum permissible error of the measurement of the counting rate shall not be greater than the estimated error of prediction that results from the use of the calibration relationship. Obviously, the error of prediction depends on the precision of the experimental methods used in measuring the moisture content of the soil in the standards. Analyses of available data show that, with the utmost in precision obtained by determining the weight of the entire body of soil in which the count rate is obtained, the error of prediction may be as low as 0.6 percent of moisture by volume. A more typical value, which pertains to the measurement of the moisture content by means of taking volumetric samples, is between 1 and 2 percent of moisture by volume. A statistical analysis of several calibration relationships that have been reported in the literature indicates errors of prediction in excess of 2 percent.

For purposes of further discussion it will be assumed that the error of prediction is 1.0 percent of moisture by volume. It is highly important to realize that this error cannot be diminished by additional measurements, longer counting times, stronger sources, or anything pertaining to improving the measurement of the count

rate. The only method whereby this error can be reduced is by procuring more calibration points and by increasing the precision with which the moisture content in the calibration procedure is established. It will also be assumed that the neutron probe must be designed in such a way that the error of counting rate measurement should not exceed the equivalent of 1.0 percent of moisture by volume. Then it may be stated that the counting rate is proportional to the source strength and to the moisture content as follows:

$$N = e \times S \times \theta \qquad [1]$$

in which N is the count rate in counts per second, S is the source strength in millicuries, θ is the moisture content as a volume fraction, and e is a proportionality factor that is measured in counts per second per millicurie and per unit of moisture, which could appropriately be called the efficiency. When this relationship is used to predict the moisture content from the calibration the equation is rewritten as follows:

$$\theta = N/(e \times S).$$

The standard error of θ then equals

$$\sigma_\theta = \sigma_N/(e \times S).$$

Knowing that the standard error of the count rate, σ_N, equals $\sqrt{N/T}$, we can write

$$\sigma_\theta = \sqrt{N}/(e \times S \times \sqrt{T}) \qquad [2]$$

in which T is the total counting time. This relationship may now be used to compute the minimum source strength required to give a standard error in the counting rate equivalent to the error of prediction. This may be done by substituting N (equation [1]) in equation [2], which gives

$$S = \theta/(e \times T \times \sigma_\theta^2). \qquad [3]$$

This simple formula points out some important considerations in the design and use of neutron probes for measuring soil moisture. First, it shows that as the moisture content of the soil increases, a proportionally larger source is required to hold the standard error of the measurement at the same absolute level. This is opposite to a widely held belief that stronger sources are required to obtain the same precision when the moisture content of the soil is low.

The formula further points out that the source strength and time of counting have the same effect. If it is desired to cut the counting time in half the source strength must be doubled and vice versa. Finally, the formula demonstrates the significance of the efficiency factor e. If the probe design has an efficiency that is twice as large as that of another, the required source strength for the same precision is only half as great. This demonstrates the importance of searching for an efficient probe design to reduce the radiation hazard from the source to the minimum required level.

In order to use the formula quantitatively, numerical values must be assigned. Since the source strength required increases with moisture content, it will be assumed that the moisture content is 0.40 volume fraction in order to get a conservative estimate. At all moisture contents below 0.40, the calculated value for S will result in a greater precision than required. The conventional period of 60 seconds is assumed for T and the value for e is determined from the calibration relation of a given probe. The value for e used here is taken from data given in the paper by Van Bavel, Nielsen, and Davidson (16). An analysis of their data for the N-104 probe shows that the value of e is 129 counts per second per millicurie. When these values

are used in the formula for the computation of $\underline{S}$, a value of 0.52 millicuries is obtained. The use of a 0.5 millicurie source, then, will result in an error of 0.01 at a moisture content of 0.40 volume fraction. This error is in addition to the error of prediction that has been discussed before, so the total error of an individual measurement on this basis would equal 0.014 in terms of volume fraction. At a moisture content of 0.10 the counting error would be less. It would amount to only 0.005 volume fraction and when combined with the same error of prediction the total standard error of the measurement would be 0.011 volume fraction--not appreciably higher than the error of prediction itself.

On the basis of the foregoing it may be concluded, then, that the use of a 1/2 millicurie source in an N-104 probe would lead, in 1-minute counting times, to counting errors that contribute only a fraction of the total error of the determination of the moisture content, provided the error of prediction of the calibration curve is 0.01 volume fraction. Increasing the source strength to 1 millicurie will, for all practical purposes, eliminate counting statistics as a significant source of error in the measurement. Any increase of the source strength above this figure must be considered as largely wasteful and unnecessarily hazardous. If, occasionally, it would be necessary to increase the precision of counting, such as in calibration procedures or in determining the standard counting rate, the obvious and simple expedient is to increase the counting time. With a scaler this is simply done by allowing the instrument to run, for example, 10 minutes instead of 1 minute; and with a rate meter this same result can be achieved by taking 10 consecutive rate meter readings instead of a single readout.

The foregoing discussion and calculation has been carried out for the case where the absolute counting rate is related to the moisture content. Often investigators prefer to work with the ratio of the counting rate in the soil to the counting rate in the standard and to express their data as well as the calibration relationship accordingly. This makes no difference in the derivation of the formula for the source strength as given provided that the standard counting rate is determined with a considerably greater precision than the counting rates in the unknown. In other words, the standard must be counted for a period of time sufficiently long or counted sufficiently many times to eliminate the counting error of the standard as a factor. A close approximation can be achieved by obtaining at least four standard counts for each count in an unknown with which the standard is to be compared to obtain the ratio.

Finally, the question arises whether differences in moisture content indicated at exactly the same location, but at different times, may not be measured with greater precision than indicated by the error of prediction. In this case the accuracy of the measured difference is determined by the standard deviation of the slope of the calibration line rather than by the absolute accuracy of the predicted values. Theoretically, the fractional error (percentage deviation) of a difference equals the fractional error of the slope. For the counting error to match this error of the difference, higher counting rates or longer counting times are required. The last consideration is predicted upon a precise duplication of all factors other than moisture content, such as location, depth, and instrument behavior.

In a recent paper, Clutter, Douglass, and Hewlett (1) have shown that site covariance greatly increases the accuracy of the measurement of soil moisture changes as contrasted to the measurement of moisture content itself. They demonstrate that with a single observation point the fractional error of the change in moisture content of a stratum is about 1 percent. Generally, this would call for longer counting times or higher count rates, as already indicated.

5. CALIBRATION PROCEDURES

5.1 General

Calibration of the neutron moisture meter consists of determining the relationship of meter readings to moisture content of the soils in which the meter is to be used. The relationship may be expressed graphically as counts per minute versus moisture content. However, for rapid and consistent results in converting meter readings to moisture content, some users of the meter have developed calibration tables from their calibration curve.

The units selected in which to express the volumetric moisture content depend upon the application that is to be made of the data. The most universally applicable unit is volume fraction (inches per inch, centimeters per centimeter or grams per cubic centimeter). Moisture content by percentage of volume is 100 times the values indicated as volume fraction.

Holmes (4) among others has pointed out that a soil sample dried at 105 C. may still contain appreciable amounts of hydrogen, which, together with other atoms in the soil, undoubtedly contribute to neutron moderation. It is proper to develop calibration curves for soil moisture based upon 105 C. drying; however, it is apparent that such a calibration curve does not include chemically bound hydrogen. (See also sec. 3.1.) Thus, the most dependable calibration curve for a neutron meter is undoubtedly obtained with the material to which it is to be applied (16). Nevertheless, for practical purposes, many investigators have found that various mineral soils had the same calibration curve.

In calibrating a meter, the investigator should keep foremost in mind that calibration measurements must be made in a soil mass of adequate size, that the moisture must be uniformly distributed within the mass, and that the moisture content on a volume basis must be accurately known. Work by Van Bavel and others (16) indicates that for calibration purposes, particularly at low moisture content, a homogeneous soil mass of at least 4-foot dimensions is required.

The question arises as to whether one should use field or laboratory calibration. Field calibration is the simplest to perform where facilities are limited. Certainly, laboratory studies are suggested if one is interested in evaluating the method. Since experimental error should be less with a laboratory procedure, the resulting calibration curve should be more accurate.

5.2 Field Calibration

The field calibration process consists of selecting sites representing a range of soil moisture conditions and installing access tubes of the type being calibrated.

A traverse of meter readings is made in each tube to determine the center point of a layer of uniform moisture-content soil. This is done by making meter readings of 6-inch depth increments until a layer of uniform moisture of at least a 2-foot thickness is encountered. The effective center of the probe is positioned in the vertical center of the layer of uniform moisture content. Then a reading having a combined length of at least 10 minutes is made. The effective center of the Nuclear-Chicago P19 probe[5] is the location of the source (which is at the midlength point of the detector tube). The effective center of the Troxler 104 probe is considered to be 4 inches from the bottom of the probe (14). When calibration measurements are made, the effective center of the probe must be at least 12 inches below the surface of high

[5] Trade names and company names are mentioned for the benefit of the reader and do not infer any endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

moisture content soils and at least 18 to 24 inches for low moisture content soils. A standardization reading of equal time length is also made. The standard should be a drum of water of at least 18 inches in diameter or other effectively infinite moderating medium. This is immediately followed by the collection of soil samples for moisture and volume determination by the gravimetric method.

A suggested procedure is to use four sampling holes spaced equally around the access tube at a radius of 6 inches or less. The soil samples used for gravimetric determination of moisture content and bulk density are collected from a soil layer no more than 10 inches thick located at the same depth as the neutron calibration reading. Stolzy and Cahoon (9) found that highest correlation was obtained between meter readings and average moisture content of a bulk volume within a soil layer 9 inches thick. They used a probe having its source at the midlength of a 1- by 12-inch detector tube, took soil samples on a 6-inch radius from the access tube, and used two 4 1/2-inch thick soil samples from each sampling hole. The common plane of contact of the two samples was on a level with the position of the effective center of the probe when the meter counts were made.

Volumetric moisture content, determined from the gravimetric soil samples, is considered to be the moisture content that corresponds to the meter reading obtained as described. Thus, one point on a calibration graph is obtained. Because of inaccuracies of the gravimetric method and the variations of natural soils, additional observations from other sites at, or near, the same moisture content are desirable. Since calibration points are required over the entire range of moisture contents to be encountered in the application of the instrument, at least 30 calibration points should be determined.

From a practical point of view, field calibration may be the simplest method. However, it is difficult to determine accurately the undisturbed volume of soil samples collected in the calibration process. Also, detailed reconnaissance may be necessary to find suitable sites having uniform moisture content for several feet of depth of the soil profile that represent various moisture contents in the range desired.

5.3 Laboratory Calibration

If painstakingly done, the laboratory calibration of a neutron meter should give points on a calibration curve that have less scatter than points determined from data collected in the field.

For a laboratory calibration using soil, it is necessary to have a container at least 4 by 4 feet (either round or square) and 4 feet high (16). Into this is placed a thoroughly mixed soil having a uniform moisture content. This soil must be placed into the container at uniform density--a difficult thing to do with fine textured soil at certain moisture contents.

Since it is difficult to obtain uniform density with some soils, it cannot be assumed that the volume of soil having the greatest influence on the calibration reading (soil immediately surrounding the access tube) is at the same density as the average of the soil in the container. Thus, with problem soils, it is desirable to take gravimetric samples from the laboratory soil mass. In these soils, for all the extra work of laboratory calibration, little is gained over field calibration if the procedure outlined for field calibration is used. (See sec. 5.2.) Instead, laboratory methods of determining bulk density should be made on the sample.

A suitable technique for determining volume of certain soils is the trimming of an undisturbed soil mass to suitable size, weighing it, and then submerging it in a vessel containing kerosene (8, p. 68). A variation of the chunk method is the coating

of the soil sample with melted paraffin and then submerging the coated sample in water to determine its volume. A correction of the displacement measurement must be made for the volume occupied by the paraffin coating.

5.4 Calibration Using Standards

A meter can be calibrated by reference to measurements made in standards, provided the standards have been previously related to soil moisture by the use of the desired type of access tubing with a probe of the same design.

The standards representing various moisture contents may be either solid types (such as sand-alum or sand-paraffin mixtures or polyethylene cylinders of various wall thicknesses) or liquid types (such as NaCl or H_3BO_3 solutions of various strengths) (3, 16). The standards that are used as calibration references should not change with time; liquid standards should be so described that they can be accurately reproduced from time to time.

A standard temperature should be adhered to in the calibration process not only because of the effect of temperature upon the performance of the neutron probe itself but because of the effect of temperature upon the properties of the standard.

5.5 Calibration by Comparison

A meter can be calibrated by direct comparison of readings of the uncalibrated meter with readings of a calibrated instrument in access tubes in the field. Although requirements of soil profiles selected for use in calibration by the comparison method need not be so stringent as the requirements for original field calibration, the depth at which comparative measurements are made should be chosen with some care. Comparisons made from readings taken at least 12 to 24 inches below the soil surface (the depth depends upon the moisture content of the soil) are the best. Also, the depths selected should be in uniform portions of moisture profiles.

Once the relationship of the two meters has been established, a calibration curve is developed for the uncalibrated meter by using soil moisture contents indicated by the calibrated instrument. This technique provides a satisfactory means of calibration, particularly when the probes being compared are of the same design. Of course, any errors in the original calibration are reflected in the calibration curve developed from it.

6. FIELD MEASUREMENTS

6.1 Equipment Checkout

6.1.1 Input Sensitivity

When a new scaler or rate meter is shipped from the factory the input sensitivity control should be at the proper setting for use with a probe supplied by the same manufacturer. The purpose of the input sensitivity setting is to exclude from the counting circuit the low energy pulses, which originate from gammas and amplifier noise. However, too high a setting not only blocks out the undesired low-energy pulses but prevents the pulses attributed to thermal neutrons from being counted. The sensitivity adjustment should not be changed unless the background count (with unshielded probe suspended in air and several feet from neutron moderating media) is more than about 25 c.p.m./m.c. The sensitivity setting should be investigated if it is suspected that the setting is too high and too many of the pulses originating from thermal neutrons are not being counted. This might happen if another type of probe was previously used.

A drop-off of meter counts with time, with the same probe, would probably be on account of another cause such as failing detector tube.

6.1.2 High Voltage Setting

The high voltage setting of the scaler may have to be adjusted as its use is changed. Also, the position for the high voltage setting may change after repair of the equipment. The first step in selecting the proper high voltage setting is to determine the count rate obtained at various voltage settings when the scaler is connected to the probe in the shield (or other standard) held at standard temperature. To do this, the scaler, with probe connected, is turned on as for making field measurements and the voltage control setting is decreased until a count rate of one-quarter of normal or less is observed. A timed 1-minute reading is made at this setting. The reading is recorded and plotted on a graph relating counts to voltage setting. Another reading is made at a 25-volt higher setting. The process is continued until a plateau of count readings is represented on the graph. The proper operating voltage is on the plateau, about 50 to 75 volts greater than the knee of the curve. A record should be made of the voltage selected, and the graph relating counts to voltage setting should be saved for future reference.

6.1.3 Overall Performance

Finally, it is important to establish whether the overall performance of the neutron meter has been affected by repairs and adjustments of the system. This check is made by making readings in known standards. The standards may consist of (1) a background count in the air, (2) a count in the probe shield, and (3) a count in a drum of water. If desired, standards made of paraffin, plastic, or other moderating media may be used for this purpose (3). It is imperative that the standards be used in the same way and in the same environment each time. Also, they must be used at an established temperature and removed from moderating media. The shield, or standard, in which the measurements are being made should be at least 2 feet away from neutron moderating media and should be more than 15 feet from another source of radiation, such as another neutron probe.

If the count rates in the various standards are proportionally the same as they were at the time the calibration curve was established for the instrument, the calibration curve is still valid provided some form of the count-ratio technique is used in determining moisture content.

If the new count rates are no longer proportional to their original values throughout the entire range of counts representing the moisture range, then the original calibration curve cannot be used. It may be that the instrument is not now in proper repair. If it is established that the instrument is in operating order, then a revision of the calibration curve is required.

6.1.4 Temperature Effects

Most currently available scalers, rate meters, and preamplifiers show only slight temperature effects. However, temperature affects the readings made in the shield of at least one make of instrument. Apparently this phenomenon is related to the fact that the lead-paraffin shield is not of infinite extent. The small dimensions of the shield result in a considerable escape of neutrons. As the temperature increases, there is a decrease in the number of thermal neutrons counted by the instrument when the probe is in the shield (middle curve fig. 10). However, with one of four lead-paraffin shields investigated the count rate increased with temperatures above 90 F. up to a point. This was possibly caused by a change of the physical state of the paraffin above 90 F.

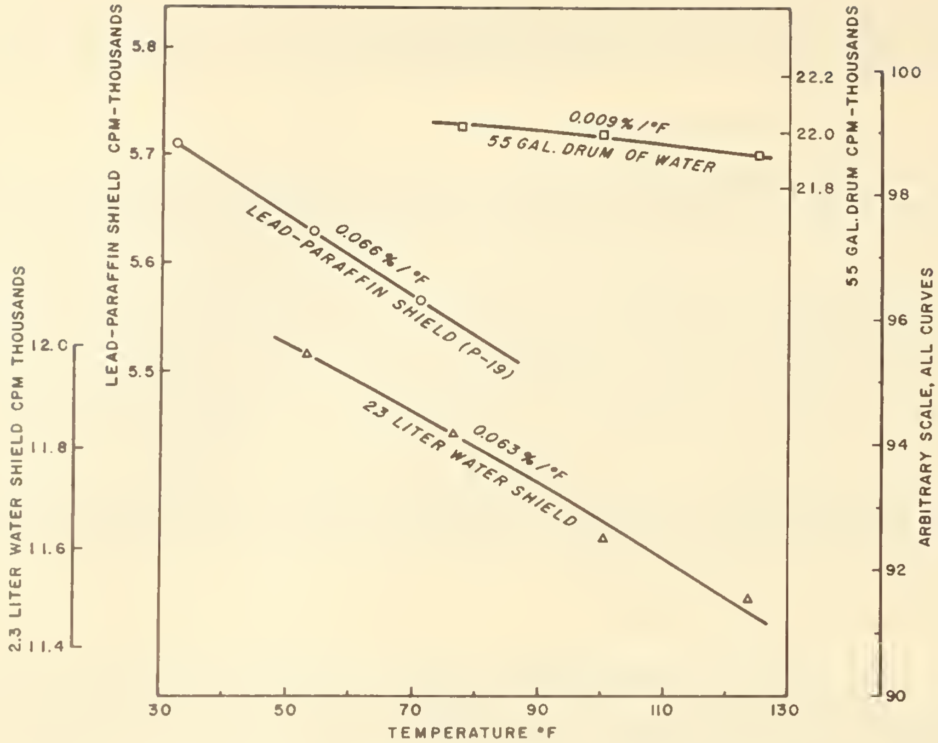

Figure 10. --Effect of temperature of standard on neutron count rate with three different standards.

A 55-gallon drum filled with water is a better standard than the lead-paraffin probe shield (upper curve of fig. 10). Readings in a small shield containing only water are affected by temperature in much the same way as are readings in a lead-paraffin shield. The data obtained from a shield 13 cm. in diameter by 21 cm. long that contained 2.3 liters of water are shown in the lower curve of figure 10. The counts obtained in the water shield were equivalent to a soil moisture content of over 60 percent by volume.

When moved from one environmental temperature to another, the lead-paraffin shield changes temperature gradually. When the probe in its shield is moved from one environment to another with a temperature difference of 40 F. or more, 6 to 10 hours are required before stable readings are obtained. The slow heating or cooling of the shield is attributed to the low heat conductivity of paraffin and the large heat capacity of the assembly. In contrast to readings in the lead-paraffin shield, stable readings are obtained within 12 minutes from the time the probe alone is immersed in a drum of water and its temperatures are different by as much as 50 F.

This suggests that standardization readings made in the lead-paraffin shield could be unreliable and might increase the error when the count-ratio method is used, rather than decrease it.

6.1.5 Standardization Counts

If the lead-paraffin shield cannot be relied upon as a standard in the field, two other solutions are possible. One would be to transport a drum of water to the field for use in making standardizing readings from time to time for use in the count-ratio technique. A container of water 18 by 18 by 18 inches would do, as it approximates an infinite body for this purpose.

The other solution would be to dispense with standardizing readings in the field and rely upon standardizing readings made in the laboratory at least twice a day; at the beginning and end of the day's use of the meter. The standard used in the laboratory should also be large enough to minimize the escape of neutrons, thus rigid temperature control would be unnecessary. Both the field and the laboratory standardization units should be made so as not to deteriorate with time and thus avoid undesirable change on the thermal neutron count received in them.

Many neutron meters in proper adjustment show practically no drift during the course of a day's use in the field when comparisons are made in standards that are not affected by temperature. However, for long-term studies it is necessary to adjust data for changes in neutron counts that result from gradual changes in the timing equipment of scalers, decreased efficiency of the detector tube with age, variation in counting rate due to replacement of electronic parts in the meter, and similar factors.

Thus, for many applications it may be possible to dispense with standardization readings in the field, if daily standardization readings are made in the laboratory for use in correcting for long-term drift in the performance of the instrument.

Laboratory standardization readings should be of longer duration than field standardization readings made periodically throughout the day so as to minimize statistical counting errors. A standardization counting period equal to 4 or 5 times the length of individual soil moisture readings may be adequate where frequent field standardization readings are averaged; however, a laboratory standardization counting period for many applications should be equal to at least 10 times the length of individual soil moisture readings. This is particularly true where the meter is used to determine moisture content of a deep soil profile. The meter should be allowed to warm up before standardization counts are taken. Some meters require but a few minutes to warm up before they reach stable performance.

6.1.6 Daily Equipment Checkout

The performance of the scaler timing switch should be tested before each use of the instrument. This can be done easily with scalers equipped to count alternating-current line frequency. A comparison of alternating-current cycles counted from one switch-timed interval to another gives an idea of the ability of the timer to reproduce the length of counting period.

To insure that the neutron meter is in operating order before it is taken to the field, it is suggested that the instrument be operated on battery power with the probe in a standard.

Records of these daily standardization readings and the check out readings of the timer are useful in understanding long-range drift of instrument performance. The checkout readings made in the laboratory can also be used in lieu of standardization readings in the field. This is discussed in section 6.1.4.

6.2 Field Procedure

This section briefly enumerates measurement techniques that follow logically from the facts set forth in the previous sections. It is assumed that the equipment is checked out by means of a standard not subject to change.

In the field one can work with or without a (portable) standard. If a standard is not used, it is only necessary to measure the count rate at the depths desired. The first step is to choose a convenient time interval. When working with a mechanical timer, 1 minute is about the least amount of time that can be measured accurately.

Electrical timers are more accurate and can be used down to 15 seconds. There is little practical value in reducing the time interval much further since other operations must be performed as well.

If the time interval is selected first, the required count follows from the accuracy of the calibration by means of formulas [1] and [2] on page 20. This count may vary from a maximum of 4,000 to 5,000 for accurate calibrations to lower figures as the dependability of the calibration relation decreases. Given a fixed probe design and source strength, it is possible to determine, by the same method, how much time is required to obtain the necessary count.

The next item to be selected is the depth intervals at which measurements should be made. With presently available equipment, there appears to be no advantage in measuring more frequently than every 6 inches, for reasons to be given in the following section. Cursory information may be had from measurements every 12 inches.

Finally, if a portable standard is used, standard counts before and after each series of measurements can increase the accuracy when the equipment is subject to slight drift as a result of changes in temperature or battery voltage.

However, one must be absolutely certain that the standard itself is not changeable. Otherwise, more harm than good will be accomplished. It appears that certain paraffin standards are subject to temperature effects. They cannot, therefore, be used as field standards. Water standards are excellent for this purpose.

Generally, neutron equipment performs reproducibly enough not to require adjustment on the basis of a field standard. Nevertheless, field checks with a standard certainly increase the confidence that one has in the use of the methods and they may remove doubts when the data are erratic or unusual.

6.3 Soil Heterogeneity

A better measure of soil moisture is generally possible with a single neutron observation than with a single gravimetric sample. However, under some circumstances the large sphere of influence of the neutron technique becomes a disadvantage. Such a case occurs when measurements are made at shallow depths in the soil. The irretrievable loss of neutrons from the soil into the air results in a lower meter reading than is characteristic for the particular moisture content of the shallow soil. (fig. 11).

Neutron meter readings are not completely free of this air-soil interface effect until the effective center of the probe is as much as 20 inches below the soil surface; the depth depends upon moisture content. The drier the soil, the greater is the depth to which the air-soil interface effect extends. Generally, the wetter the soil, the greater is the air-soil interface effect in terms of absolute error which may exceed 1 inch of moisture. In soil moisture investigations, other methods of sampling the surface layer of soil should be used and some means of correcting neutron readings at the shallow depths should be used.

The interface effect takes place to a modified extent within the soil mass whenever the moisture content changes with depth. Thus in a stratified profile, when the sphere of influence includes soil from more than one stratum of different moisture contents, the reading will be influenced and will not indicate true moisture content. The effects of abrupt moisture changes are illustrated in the lower portion of figure 11. The readings taken in a dry soil are biased upward as a wet layer is approached. Conversely, meter readings taken in a wet layer are biased downward as a dry layer is approached.

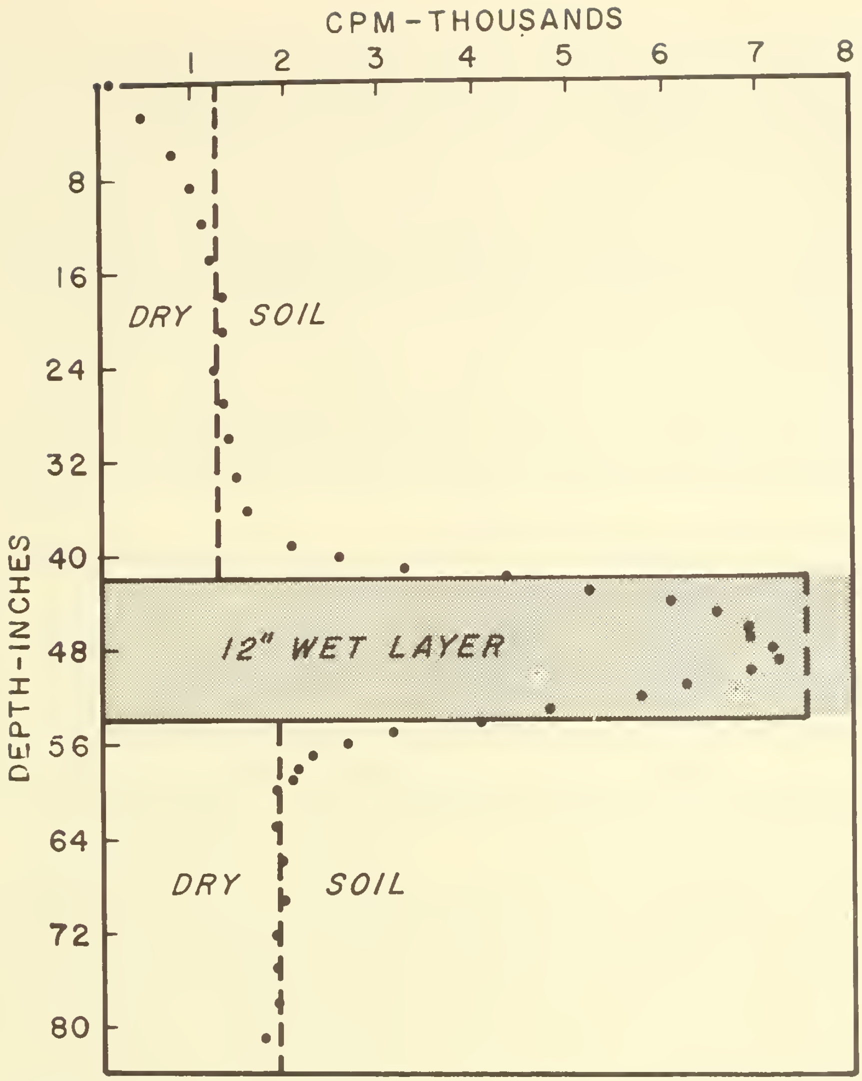

Figure 11. --Neutron count rate as affected by soil heterogeneity. The vertical dashed lines are estimates of what the meter readings would have been if there had been no interface effects. Data from (7).

Fortunately, errors of measurement are somewhat compensating in proximity to horizontal interfaces within soil profiles. In the case illustrated, the underestimates of moisture content in the wet soil were partially compensated for by overestimates in the dry. However, the net effect is a slight underestimate of the moisture content of the profile. This downward bias was true of all interfaces investigated by Lawless and others (7), when the depth increment used was 6 inches or less.

Errors in estimating profile moisture content varied over a range several times greater when 12-inch sampling increments were used than when 6-inch increments were used. However, generally speaking, the estimates of moisture content for the stratified profiles were also underestimated when 12-inch increments were used. Exceptions sometimes occurred when 12-inch increments were used in situations such as when one of the points measured happened to fall in the center of a wet layer. In this situation, the indicated moisture content of the profile (excluding the surface layer) was sometimes a little greater than actual.

Although individual readings in a stratified profile may be considerably in error, it appears that errors due to a wet-dry soil interface encountered at depth may be disregarded in practical applications where one is mainly interested in knowing changes in total profile moisture content from time to time. This is particularly true if depth increments used in the measurements are 6 inches or less.

Observations made at interfaces suggest that neutron readings are also biased downward in the presence of a moisture gradient even though the gradient is uniform. Unless the moisture gradient is quite steep, probably this error can generally be overlooked in studies concerned with determining differences from time to time.

6. 4 Handling Equipment

Common sense procedures for handling the neutron meter have been developed by keeping two main objectives in mind. These procedures will contribute much to the satisfactory performance of the meter:

A. Keep radiation exposure to a minimum
   1. Store probe in an adequate shield under lock and key. (Radiation level in unrestricted area should not exceed 1 mr/hr.)
   2. Always keep probe shielded except when in use.
   3. Always maintain maximum distance between personnel and probe.
   4. Never handle with bare hands the part of the unshielded probe that is opposite the source.
   5. See that probe, shield, and probe box are plainly labeled that they contain radioactive contents.
   6. Consider supplementary shielding when probe is transported in automobile for long distances.

B. Avoid physical damage to instrument
   1. Prevent impact shock to instrument. Transport in padded container.
   2. Avoid subjecting instrument to extremes of temperature. The performance of all electronic devices is affected by temperature. The neutron meter is no exception.

7. FIELD INSTALLATIONS

7. 1 Required Number of Sites

Selection of the required number of measurement sites should be based on the same principles that govern the number of sites required for gravimetric moisture sampling; however, factors peculiar to the neutron meter should be taken into account as follows:

1. The neutron meter samples very nearly the same soil mass each time a moisture reading is made.
2. The neutron meter samples a larger soil mass than most gravimetric samples.
3. The number of moisture readings per day is limited by the time required for one reading.
4. It has been estimated that one neutron meter measuring site is equal in precision to seven gravimetric samples (11).
5. A minimum counting time is required to obtain the greatest possible precision (see sec. 4. 6).
6. Where neutron meter measurements replace or supplement lysimeter data, the number of measurement sites is governed by the physical size of the plot.

7.2 Access Tubes

Access holes should be lined with durable tubing to hold the dimensions of the hole constant, to exclude free water, and to provide uniform conditions for moisture measurement. The access tube should be as small as possible yet allow easy movement of the probe, have minimum wall thickness, and be made of material that does not impede the movement of neutrons.

Aluminum is practically transparent to neutrons and, therefore, is a desirable material for access tubes. Steel and other common tubing materials generally have lower neutron transmission efficiency than aluminum; however, brass, steel, stainless steel, polyethylene plastic, and galvanized steel access tubes have been used successfully when appropriate calibration curves were used.

The neutron efficiency for a given probe decreases as the diameter of the access tube increases. Cracks around the access tube increase the effective diameter of the access hole and cause inaccurate readings.

7.3 Access Tube Installation

There are at least five conditions that must be met in the placement of access tubes.

1. Soil moisture content must not be changed.
2. No void spaces should exist between the access tube and soil.
3. No mixing of soil horizons adjacent to access tubes should occur during placement.
4. No vertical flow of water should occur along the access tube from the surface or from perched water tables.
5. The bottom of the tube must be plugged to exclude free water where this is a problem.

Access tubes have been installed by placement in snug-fitting holes, predrilled by soil tube or auger that was either hand- or machine-operated. Tubes may also be placed by alternately driving the tube and augering the soil from within the tube (10), jetting with compressed air, drilling with compressed air as the drilling fluid, or by drilling with vacuum to remove cuttings from the drilled hole. The method of placing the access tube in an oversize hole and backfilling is not recommended (2).

The mechanized soil sampler with offset drive described by Jensen and others (6) is well adapted to rapid installation of access tubes to a depth of 6 feet. The machine will place tubes from 9 to 11 feet from the center of the unit. This machine is particularly valuable for studies where access tubes must be replaced each year. Under good conditions up to 10 tubes per hour may be placed to a depth of 6 feet.

Figure 12 shows the mechanized soil sampler developed by Jensen and others (6) in use in the field. Figure 13 shows the sampling tube and tip[6] used to install access tubes made of 1 1/2-inch galvanized steel electrical conduit tubing (O.D. 1.74 inches, I.D. 1.61 inches). The tip shown for the soil tube was developed for clay loam soils. It is likely that differently shaped tips will be required for sandy soils and special conditions.

A portable power driven flight auger (fig. 14) was used by Kozachyn and McHenry[7] to remove the soil inside a steel tube sunk into the ground as a caisson.

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[6] Private correspondence from M. E. Jensen, Soil and Water Conserv. Res. Div., U.S. Agr. Res. Serv., P.O. Box 758, Fort Collins, Colo.

[7] Kozachyn, John, and McHenry, J. R. A method of installing access tubes for soil moisture measurement by the neutron procedure. Sedimentation Lab., Agr. Res. Serv., Oxford, Miss., Unpub. Res. Rpt. 326. 1960.

Figure 12. --Mechanized soil sampler used in field calibration of neutron equipment.

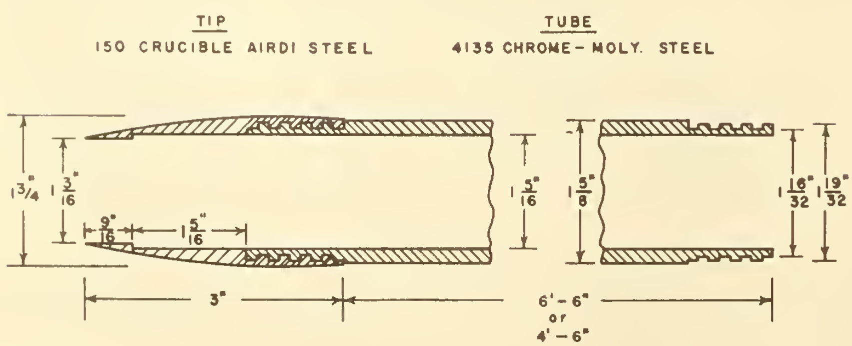

Figure 13. --Sampling tube used in field calibration of neutron equipment.

Figure 14. --Portable flight auger for installing access tubes.

The steel tube controls the diameter of the hole, helps maintain auger alignment, and reduces to a minimum the mixing of soil from different horizons. After the hole is drilled to the desired depth, the steel tube is removed and an aluminum access tube with the bottom end welded shut is inserted in the hole. This method of installation was used to install access tubes to a depth of 20 feet.

Access tubes have been successfully installed to considerable depth with various large drilling rigs. Continuous flight augers and drilling with compressed air as drilling fluid to carry cuttings to the surface have both been used in conjunction with heavy drilling equipment.

Modern air-vacuum drilling equipment removes cuttings from the hole through the inside of the drill stem immediately after cutting. This prevents mixing of soil horizons that may be a problem with some other drilling methods. Equipment with air stream velocity of 8,000 feet per minute inside the drill stem is reported by one manufacturer to be capable of drilling holes 300 feet deep.

The bottom of the access tube should be plugged when the water table is penetrated or where a rising water table might flood the hole. The plug also serves as a good reference point for depth during readings in the hole and keeps the tube from sinking into soft soil. A rubber stopper may be pressed into the bottom of the access tube after placement; however, this has not been successful in all cases. A plug welded into the end of the access tube and tested under pressure before placement insures a watertight access tube.

The clearance and alignment of the access tube should be checked by running a dummy probe down the tube after installation. The tube may be bent during installation and could cause the probe to become stuck underground. Removal of the probe, once stuck, is difficult because the probe contains delicate electronic components that should not be subjected to shock and the radioactive source presents a health hazard.

7.4 Site Preservation

The neutron meter measures the same soil volume each time a moisture measurement is desired; this is usually an advantage, but it may be a disadvantage if the sampling site is not maintained properly. Moisture data, no matter how precise, have little value if the sampling site does not represent the desired test condition. It is, therefore, very important that precautions be taken to preserve the sampling site in the desired test condition at all times.

In long-term moisture studies on cultivated fields it may be desirable to leave access tubes in place from year to year. However, tillage operations over the access tube sites are necessary to maintain test conditions similar to the whole plot. This has been done by burying access tubes below the maximum tillage depth[8]. During tillage operations the tube is plugged with a rubber stopper and tillage is performed over the site. When moisture readings are desired the tube is exposed by augering a hole over the tube. A short access pipe with a collar attached is fitted on top of the access tube to extend above the ground surface. A metal detector is useful in locating buried access tubes with magnetic properties.

In cultivated row crops, the access tubes may be placed in the row after planting. They will, however, have to be removed before starting any basic tillage operations.

In areas where vehicles operate or livestock range, access tubes should be protected from physical damage. Lawless[9] has found that terminating access tubes at the ground surface minimized damage by livestock. He also found that neoprene laboratory type stoppers make good durable plugs for the top of the access tube. A strong hook should be placed in the stopper so that it can be extracted if a large animal should trample it. Lawless also reports that there will be little or no livestock milling around an access tube if markers or stakes are not left at the site. Access tubes can be easily located by measuring from reference points placed some distance away from the tube.

Access tubes extending above the ground surface should also be capped or plugged to exclude rain water and to keep insects, rodents, and other stray material out of the tube. Baby food or fruit juice cans make good covers where frequent readings are made and large animals are not a problem.

Where frequent soil moisture measurements are made, ground surface trampling by the operator may change the environment around the site. This may be reduced by using a Go-Cart (fig. 15) that carries the equipment and provides a convenient working environment for the operator. Bridges can be used to prevent trampling and provide access to tubes surrounded by water.

8. EVALUATION OF DATA

Neutron meter equipment now in use will show slightly different count rates for constant moisture content over a period of time. This is partly due to the gradual change in behavior of certain component parts of the equipment. The "ratio method" for reporting readings of the neutron meter eliminates most errors due to the change in behavior of equipment components. The "ratio" is defined as the quotient obtained by dividing readings made in soil by a standard reading. The standard reading may be obtained in a paraffin shield or in a water standard.

Recent investigations show that readings made in paraffin standards may be influenced by the temperature of the standard (see sec. 6.1.4). Where practical, a water standard is recommended instead of the paraffin standard. Precautions should be taken to insure standard conditions for the standard count in either paraffin or water. Since the neutron meter is subject to random counting errors, it is recommended that sufficient counts be taken in the standard to reduce random counting error to a small value (see sec. 6.1.5).

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[8] Private correspondence from H. V. Eck, Soil and Water Conserv. Res. Div., U. S. Agr. Res. Serv., Southwestern Great Plains Field Station, Bushland, Tex.

[9] Private correspondence from G. Paul Lawless, Soil and Water Conserv. Res. Div., U. S. Agr. Res. Serv., P. O. Box E, Lompoc, Calif.

Different neutron meters generally give different readings for the same moisture content; therefore, it is necessary to have a calibration equation or table for each unit. Moisture content can be calculated from an equation derived for each meter; however, this is a rather laborious task. Tables calculated from the calibration equation are more convenient for converting field data to the desired moisture units. Where the standard count does not change appreciably, a table can be used to convert counts per minute directly to moisture content.

The neutron meter indicates the concentration of water in the soil mass. The term "volume fraction" seems most appropriate for describing this dimensionless term. The equivalent depth of water per given depth of soil can be obtained by multiplying the volume fraction by the specified depth of the soil. Thus, the results can be expressed in terms of inches per foot (inches of water per foot of soil) or centimeters per meter (centimeters of water per meter of soil), which are used in precipitation and evapotranspiration measurements.

One of the advantages of the neutron meter is the rapid calculation of moisture content. This advantage is particularly useful when the raw data are converted from counts per second to moisture values in the field and immediately plotted on graphs or tabulated. This procedure enables the operator to check data that do not conform to the expected pattern and correct errors in the field or confirm unusual readings. The reduction of the raw data in the field uses the operator's time more efficiently and makes the task more interesting.

Figure 15.--An operator using a Go-Cart while making neutron moisture measurements.

9. RADIATION HAZARDS AND SAFETY PROCEDURES

All radioactive substances are a potential health hazard, no matter how small the quantity. Exposure should be made as small as possible and practical. However, one should not be overly fearful or concerned about working with such materials. A thorough understanding of the hazard and the use of adequate and sensible handling procedures will safeguard one against injury.

Shielding used with commercially available moisture depth probes is a compromise between complete shielding and ease of hand carrying. Reasonably careful handling and use of moisture probes, having sources of 10 millicuries or less, will result in exposures to radiation that are within permissible limits. Actual film badge and dosimeter records accumulated by numerous workers for several years show dose rates of less than 25 mr. per week. This is considerably less than the maximum permissible weekly dose according to AEC standards. Often, this amount is not exceeded in 3 months.

Though film badges are most generally in use as personal monitors, more accurate records may be obtained with pocket dosimeters. These also permit analysis of exposure in terms of individual operations.

It should be remembered that commonly used film badges, pocket dosimeters, and GM type survey meters detect gamma radiation, but give no indication of neutron dosage. If the duration of time in proximity to the probe is kept to a minimum, the exposure to neutrons is well within the permissible limit of 20 n sec.$^{-1}$ cm.$^{-2}$ for fast neutrons. The neutron flux around an unshielded 2-mc. probe is estimated to be 1 n sec.$^{-1}$ cm.$^{-2}$ at a 1-foot distance (14).

A separate hazard is the possibility of a leak in the source. Manufacturers of radium sources take all precautions to insure a perfect and permanent seal, and leaks are extremely uncommon. Regulations require that a leak test be performed semi-annually on the sources of neutron probes.

Minimizing health hazards was considered in the development of the procedures outlined in section 6.4. Using the indicated procedures and precautions, relatively unspecialized field personnel may use the neutron method for measuring soil moisture with confidence and safety.

Authorization from the Radiological Safety Committee of the U. S. Department of Agriculture is required by personnel of the Department who wish to use nuclear instruments or radioactive materials. For the guidance of such workers, this Committee has made available the Radiological Safety Handbook (12). The handbook gives general rules governing the use of radioactive materials and radiation equipment, and refers specifically to neutron moisture probes.

10. GUIDE TO AVAILABLE EQUIPMENT

This list may not be complete and it does not constitute preference or endorsement for the equipment mentioned. Prices and description are based on information supplied by manufacturers or suppliers as of November 1, 1961.

10.1 Counting Equipment

10.1.1 Scalers:

Nuclear-Chicago 2800A (identical with Soiltest NU1)--A portable glow-tube scaler with voltage variable from 900 to 1,500 volts AC/

DC operation, variable input sensitivity. Weight, 34 pounds; price, $1,635.

Troxler 200B--A portable glow-tube scaler and rate meter combination. Voltage range is 350-900 and 1,100-1,500 volts, AC/DC operation, variable input sensitivity. Weight, 15 pounds for scaler, 12 pounds for separate battery charger; price, $1,740.

10.1.2 Rate Meters:

Kaiser-Tempe Rate Meter, Model 487, (Kaiser Aircraft and Electronics)--A portable solid-state rate meter. Voltage fixed at 1,350 volts, DC operation, variable input sensitivity, range 0-200 c.p.s. Weight, 7 pounds; price, $1,280. See also Troxler 200B in section 10.1.1.

10.1.3 Depth Probes

Kaiser, Model VMP487--A 2-mc. depth probe, 1,875" OD, complete with 30-foot cable and shield. Weight 24 pounds; price $770.

Nuclear-Chicago P19 (identical to Soiltest NU4)--A 4-mc. depth probe, 1.5" OD, complete with 25-foot cable and shield. Weight, 46 pounds; price $1,360.

Troxler 104--A 2-mc. depth probe, 1.875" OD, complete with 20-foot cable and shield. Weight, 30 pounds; price $1,000.

10.1.4 Surface Probes:

Nuclear-Chicago P21 (identical to Soiltest NU3)--A 4-mc. surface probe utilizing multiple BF_3 tubes with a 20-foot cable and standard. Weight, 63 pounds; price, $1,880.

Troxler 104-115--Surface moisture adapter, including standard and a 104 moisture probe without shield. Weight, 19 pounds; price, $1,200.

10.1.5 Suppliers Addresses:

Kaiser Aircraft and Electronics, P. O. Box 9098, Phoenix, Ariz.

Nuclear-Chicago Corp., 333 East Howard Avenue, Des Plaines, Ill.

Soiltest, Inc., 4711 West North Avenue, Chicago 39, Ill.

Troxler Electronic Laboratories, Inc., P. O. Box 5253, Raleigh, N. C.

10.2 Machinery for Access Tubing Installation

10.2.1 Offset drive soil sampling machine for placement of access tubes:

Frank L. Howard Engineering Co., 4921 East Olympic Boulevard, Los Angeles 22, Calif.

10.2.2 Soil augering equipment for placement of access tubes:

Haynes Manufacturing Co., P. O. Box 191, Livingston, Tex.

Mobile Drilling, Inc., 960 North Pennsylvania Street, Indianapolis 4, Ind.

Soiltest, Inc., 4711 West North Avenue, Chicago 39, Ill.

Testlab Corp., 2734 Laramie, Chicago 39, Ill.

10.2.3 Vacuum drilling machines for placement of access tubes:

Houston Tool Co., P. O. Box 251, Santa Susana, Calif.

11. LITERATURE CITED

(1) Clutter, J. L., Douglass, J., and Hewlett, J. D.
Instrumental and soil moisture variance using the neutron scattering method. Soil Sci. [In press. 1963]

(2) Goldberg, Irving, Trescony, L. J., Campbell, J. S., Jr., and Whyte, G. J.
1955. Measurement of moisture content and density of soil masses using radioactivity methods. In Proc. Third Natl. Conf. on Clays and Clay Min., Natl. Acad. Sci. Natl. Res. Council Pub. 395: 516-548, illus.

(3) Hauser, V. L.
1962. Paraffin standards for neutron meter calibration. Agr. Engin. 43: 88-89, illus.

(4) Holmes, J. W.
1956. Calibration and field use of the neutron scattering method of measuring soil water content. Austral. Jour. Appl. Sci. 7: 45-58, illus.

(5) ________ and Jenkinson, A. F.
1959. Techniques for using the neutron moisture meter. Jour. Agr. Engin. Res. 4: 100-109, illus.

(6) Jensen, M. E., Sletten, W. H., and Ochs, R. L.
1960. Mechanized soil sampler with offset drive. Amer. Soc. Agr. Engin. Trans. 3: 22-24, illus.

(7) Lawless, G. P., MacGillivray, and Nixon, P. R.
Moisture interface effects upon neutron meter readings. Soil Sci. Soc. Amer. Proc. [In press, 1963]

(8) Spangler, M. G.
1960. Soil engineering. Ed. 2. Scranton, Pa.

(9) Stolzy, L. H., and Cahoon, G. A.
1957. A field-calibrated portable neutron rate meter for measuring soil moisture in citrus orchards. Soil Sci. Soc. Amer. Proc. 21: 571-575, illus.

(10) Stone, J. F., Kirkham, D., and Read, A. A.
1955. Soil moisture determination by a portable neutron scattering moisture meter. Soil Sci. Soc. Amer. Proc. 19: 419-423, illus.

(11) __________, Shaw, R. H., and Kirkham, Don.
1960. Statistical parameters and reproducibility of the neutron method of measuring soil moisture. Soil Sci. Soc. Amer. Proc. 24: 435-438. illus.

(12) United States Department of Agriculture.
1961. Radiological safety handbook. 24 pp., illus. Radiological Safety Com.

(13) U. S. Public Health Service.
1960. Radiological health handbook. Rev. ed., 468 pp., illus.

(14) Van Bavel, C. H. M.
1958. Measurement of soil moisture content by the neutron method. U. S. Agr. Res. Serv. ARS 41-24, 29 pp., illus.

(15) ________
1961. Neutron measurement of surface soil moisture. Jour. Geophys. Res. 66: 4193-4198, illus.

(16) ________, Nielsen, D. R., and Davidson, J. M.
1961. Calibration and characteristics of two neutron moisture probes. Soil Sci. Soc. Amer. Proc. 25: 329-334, illus.

(17) ________, Underwood, Newton, and Swanson, R. W.
1956. Soil moisture measurement by neutron moderation. Soil Sci. 82: 29-41, illus.